

Conformal Spiral Antenna Based on Conductive Textile Threads for Load-Bearing Applications

Asimina Kiourti, Jingni Zhong and John L. Volakis
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Abstract: Broadband antennas are highly attractive for load-bearing applications, such as airborne and wearables. However, antenna design for such applications is very challenging due to requirements for 1) conformality, 2) lightweight, 3) robustness, and 4) tolerance to extreme weather conditions.

With this in mind, we present a novel 10:1 bandwidth conformal antenna based on a new class of conductive textiles (see Fig. 1). The antenna is a cavity-backed Archimedean spiral, 160 mm in diameter. It was ‘printed’ via automated embroidery of metal-coated polymer threads (E-threads), down to 0.12mm in diameter (A. Kiourti, C. Lee and J.L. Volakis, IEEE Antennas Wireless Propag. Lett., 2015). Doing so, the embroidery geometrical precision is as high as 0.1mm, viz. similar to typical Printed Circuit Board (PCB) designs. To enhance robustness, high-strength Kevlar fabric ($\epsilon_r = 2.6$, $\tan\delta = 0.006$) was employed as the antenna’s substrate. Kevlar is a lightweight, low-loss, abrasion- and heat-resistant material, making it suitable for extreme and flexible applications. The textile ground plane was placed at a distance of $\lambda_{\text{low}} / 40$ from the spiral’s surface, where λ_{low} refers to the wavelength at the lowest operational frequency (in this case, 0.3 GHz). Two 180 Ω resistors were soldered at the spiral ends to suppress wave reflections.

As per design, the textile antenna exhibits a 10:1 bandwidth (VSWR < 2), operating from 0.3 to 3 GHz. It also delivers a consistent circularly polarized realized gain of 8 dBi. This gain hold for most of the 10:1 band except near 300 MHz. Specifically, at low frequencies, the resistive termination decreases the antenna efficiency.

At the conference we will present spiral performance measurements, and several other antenna examples using the aforementioned embroidery process.

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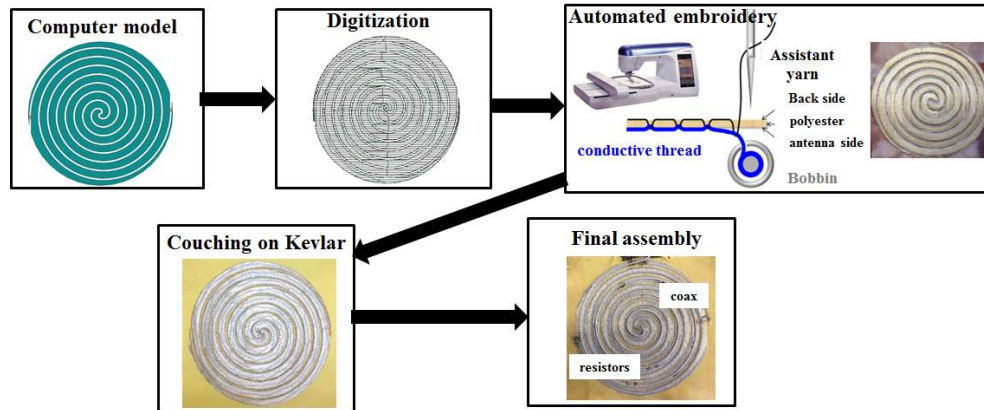


Fig. 1. Fabrication process of the proposed 10:1 bandwidth textile-based spiral.

Keywords: Conformal Spiral Antenna, Conductive Textile Threads, Load-Bearing Applications.



Asimina Kiourti has been with The Ohio State University ElectroScience Laboratory since 2013, where she is currently a Senior Research Associate. Prior to that, she received the Ph.D. degree in Electrical and Computer Engineering from the National Technical University of Athens, Greece (2013) and the M.Sc. degree from University College London, UK (2009).

Dr. Kiourti has (co-)authored more than 25 journal papers, more than 50 conference papers, and 6 book chapters. Her research interests include neurosensing and other medical sensing, antennas for medical applications, RF circuits, bioelectromagnetics, and flexible textile and polymer-based antennas.

Dr. Kiourti has been the recipient of more than 40 awards and scholarships, including the IEEE Engineering in Medicine and Biology Society (EMB-S) Young Investigator Award for 2014, the IEEE Microwave Theory and Techniques Society (MTT-S) Graduate Fellowship for Medical Applications for 2012, and the IEEE Antennas and Propagation Society (AP-S) Doctoral Research Award for 2011. In 2004, she received personal recognition from the President of Greece for ranking first in the Achaia prefecture (>300,000 inhabitants) during the Pan-Hellenic University Entrance Exams.

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John L. Volakis (S'77–M'82–SM'89–F96) was born in Chios, Greece, on May 13, 1956 and immigrated to the USA in 1973. He received the B.E. degree (summa cum laude) from Youngstown State University, Youngstown, OH and the M.Sc. and Ph.D. degrees from The Ohio State University, Columbus, in 1979 and 1982, respectively. He started his career at Rockwell International (1982–1984), now Boeing

Phantom Works. In 1984, he was appointed Assistant Professor at the University of Michigan, Ann Arbor, becoming a full Professor in 1994. He also served as the Director of the Radiation Laboratory from 1998 to 2000. Since January 2003, he has been the Roy and Lois Chope Chair Professor of Engineering at The Ohio State University and also serves as the Director of the ElectroScience Laboratory. He has carried out research on antennas, medical sensing, computational methods, electromagnetic compatibility and interference, propagation, design optimization, RF materials and metamaterials, RFIDs, milli-meter waves and terahertz, body-worn wireless technologies, and multi-physics engineering. His publications include 8 the books. Among them are: Approximate Boundary Conditions in Electromagnetics (IET, 1995), Finite Element Methods for Electromagnetics (Wiley–IEEE Press, 1998) the classic 4th ed. Antenna Engineering Handbook (McGraw–Hill, 2007), Small Antennas (McGraw–Hill, 2010), and Integral Equation Methods for Electromagnetics (SciTech, 2011)]. His papers include about 370 journal papers, about 700 conference papers, and 25 book chapters. He has also written several well-edited coursepacks, and has delivered short courses on antennas, numerical methods, and frequency selective surfaces.

Dr. Volakis received the University of Michigan (UM) College of Engineering Research Excellence award, in 1998, and in 2001 he received the UM, Department of Electrical Engineering and Computer Science Service Excellence Award. In 2010 he received the Ohio State University Clara and Peter Scott award for outstanding academic achievement. Also, in 2014 he received the IEEE AP Society distinguished achievement award and the IEEE AP Society C-T Tai Educator award. He was listed (2004) by ISI among the top 250 most referenced authors. His mentorship includes over 80 doctoral students/post-docs with 30 of them receiving best paper awards at international conferences. He was the 2004 President of the IEEE Antennas and Propagation Society and served on the AdCom of the IEEE Antennas and Propagation Society from 1995 to 1998. He also served as Associate Editor for the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION from 1988–1992, Radio Science from 1994–1997, and for the IEEE Antennas and Propagation Society Magazine (1992–2006), the Journal of Electromagnetic Waves and Applications and the URSI Bulletin. Further, he served on the IEEE wide and AP Society Fellows evaluation committee. In 1993 he chaired the IEEE Antennas and Propagation Society Symposium and Radio Science Meeting in Ann Arbor, and Co-Chaired the same Symposium in 2003 at Columbus, OH. He was elected Fellow of the IEEE in 1996 and is also a Fellow of the Applied Computational Electromagnetics Society (ACES). He is a member of the URSI Commissions B and E, and currently serves as the Chair of USNC/URSI Commission B.

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“Conformal Spiral Antenna Based on Conductive Textile Threads for Load-Bearing Applications”

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Outline

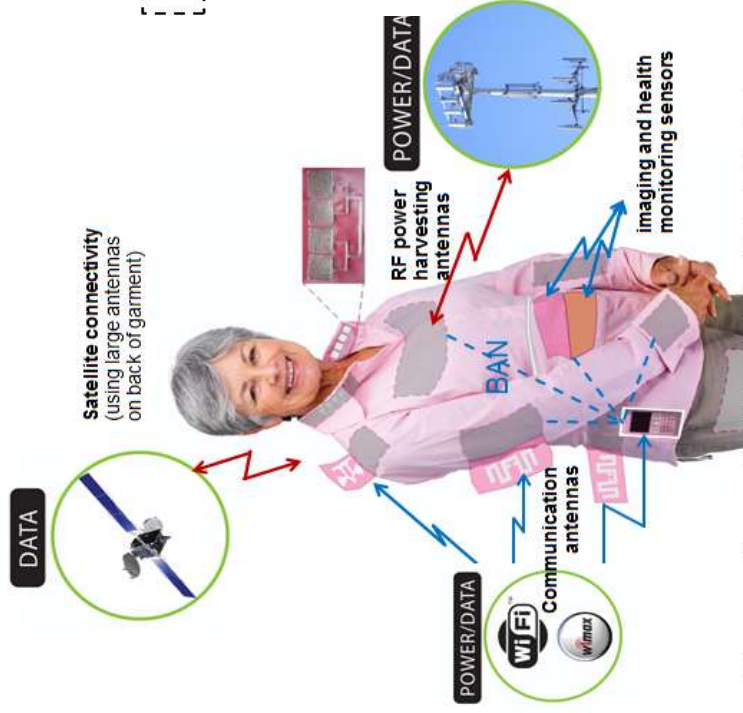
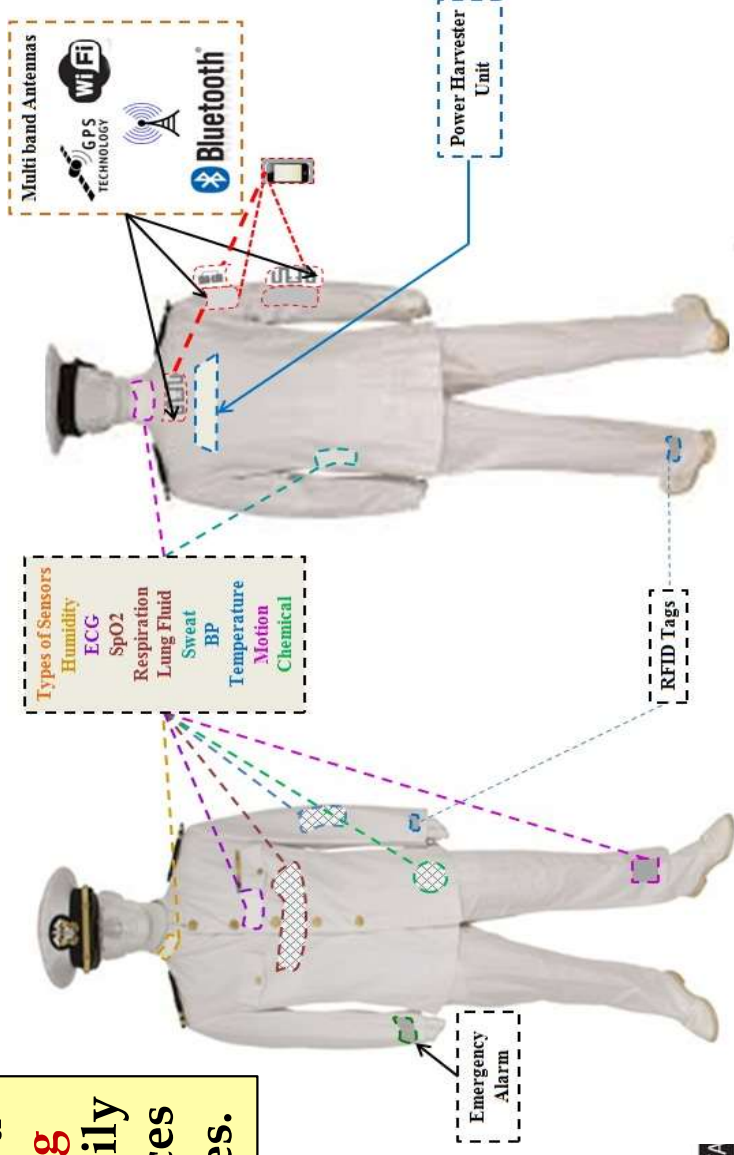
- **Objective:** 10:1 bandwidth (300MHz-3GHz) conformal spiral antenna on textiles
- **Technology:** flexible E-threads on polymer substrates
- **Proposed Antenna:** Design and Fabrication
- **Antenna Performance:**
 - *RF Performance*
 - *Mechanical / Thermal Testing*



THE OHIO STATE UNIVERSITY

Vision: Smart Wearables for Healthcare, Military, Emergency, and Communication Applications

Our patented textile technology is a **new paradigm in low-cost weaving within the fabrics** and can be readily embedded with a variety of functionalities. to realize all sorts of functionalities.



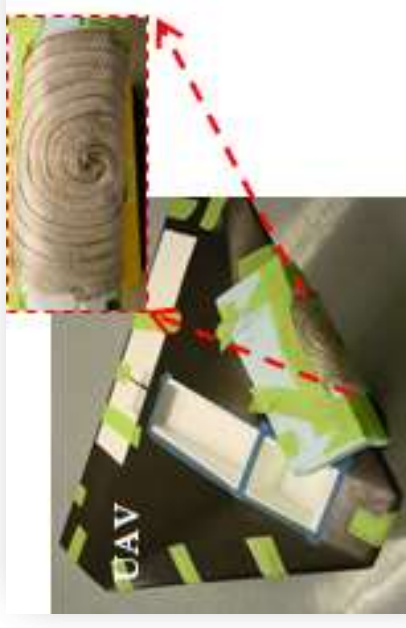
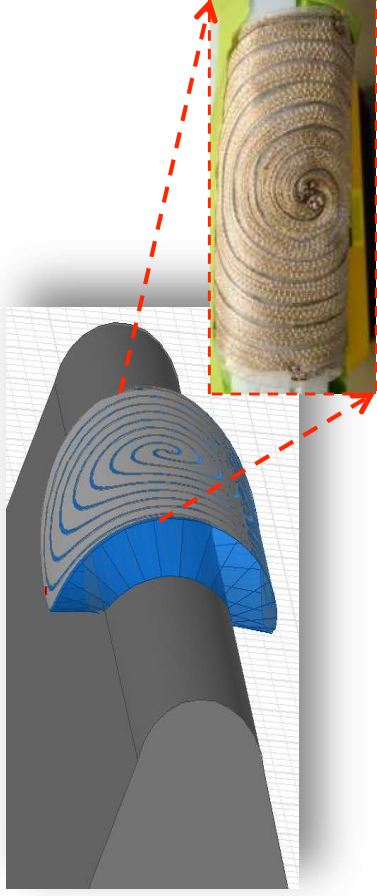
*All sensor patches are colored differently for visualization in this chart.

- Wirelessly transmit **position, motion, identity, and healthcare status**
- Notify of **damage/emergency control events**
- **Comfortable and lightweight** for unobtrusive integration into garments
- **Durable and robust** to withstand daily wear

Objective

OBJECTIVE: Develop **10:1 bandwidth (300 MHz – 3 GHz) spiral antenna** for load-bearing applications, (e.g., wearables and airborne), that addresses the requirements of:

- Conformability
- Lightweight
- Robustness
- Tolerance to extreme weather conditions

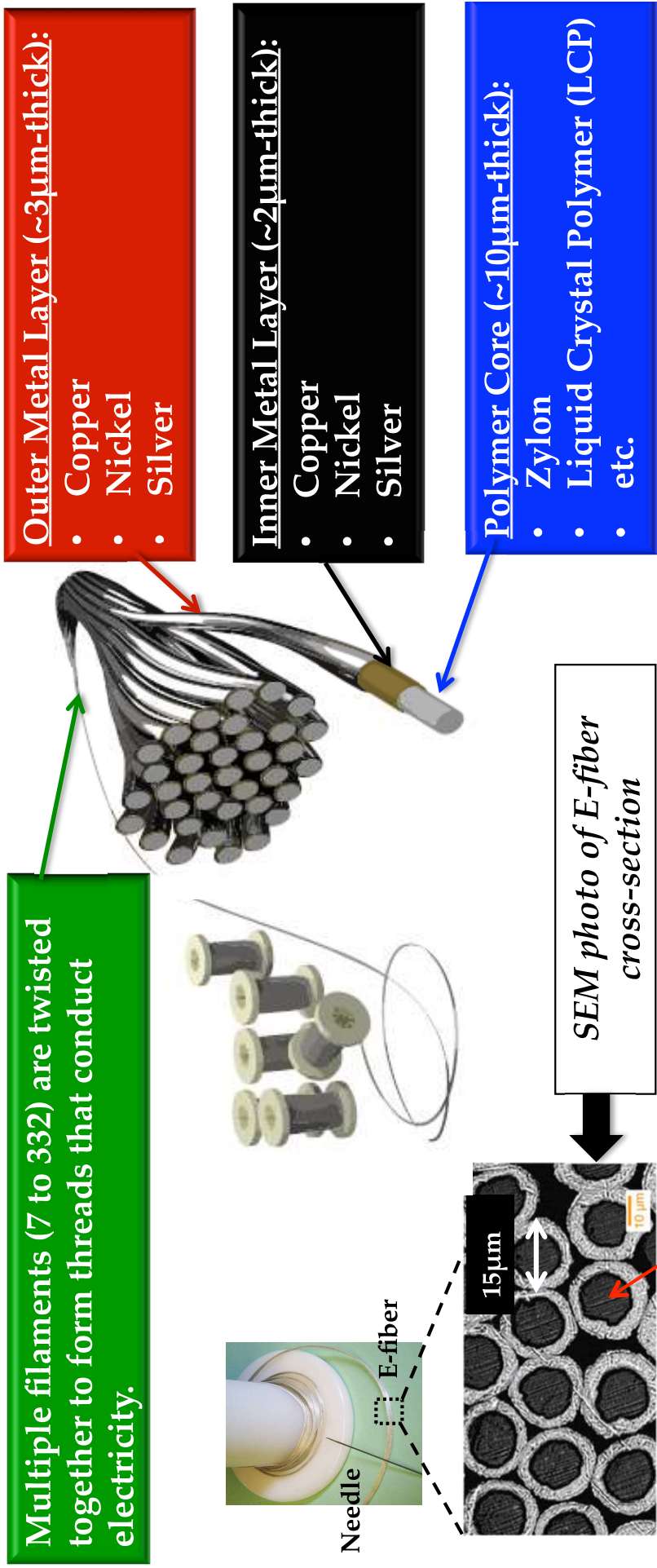


Technology Key Feature: Flexible E-threads

Conductive E-threads

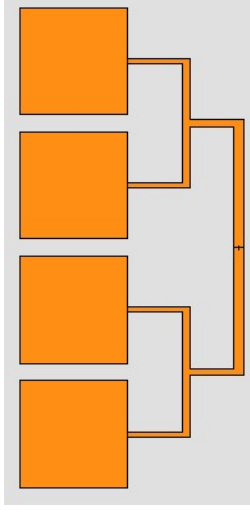
- Metal-coated polymer filaments, bundled into groups of 7s to 600s to form threads. Each thread may be **down to ~0.12mm in diameter**.
- Excellent **flexibility, strength, conductivity, and thermal stability**.

Multiple filaments (7 to 332) are twisted together to form threads that conduct electricity.



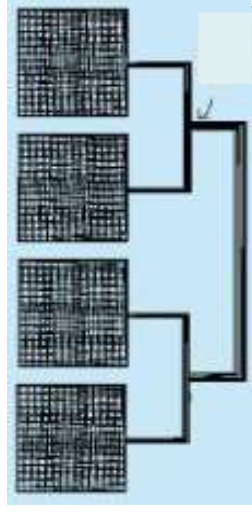
Embroidered Textiles Using E-threads

HFSS model

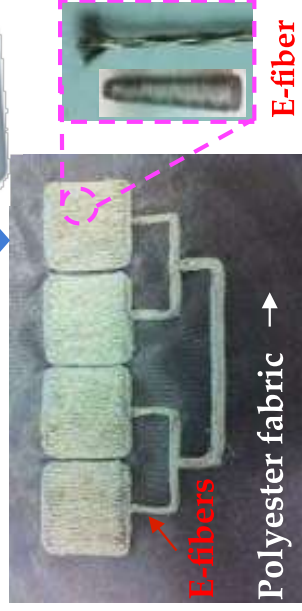


Export to specific
computer program

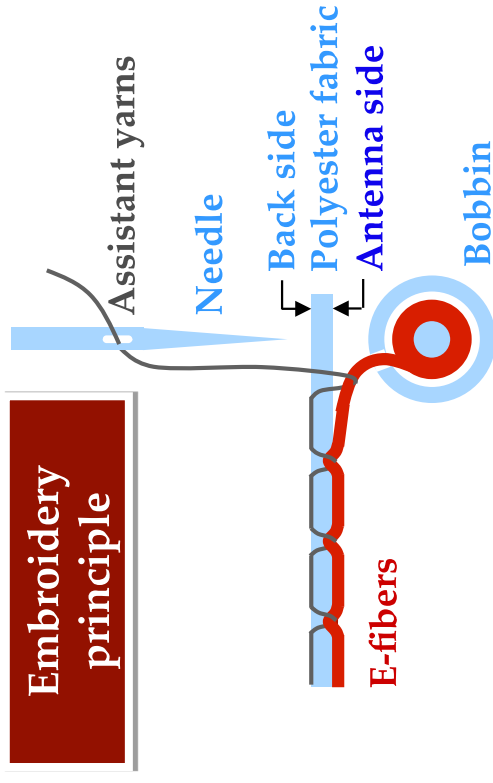
Digitization



Embroidered
antenna



- Export antenna design pattern
- Digitize thread route for automated embroidery
- Embroider on fabrics using braided or twisted E-fibers (embroidery process uses assistant non-conductive yarns to “couch” down E-fibers)

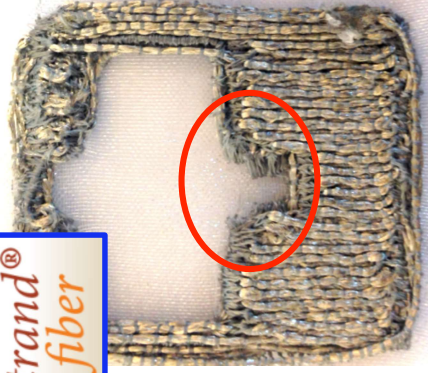




New Embroidery Process: Achieves Geometrical Precision as high as 0.1mm

Former Technology

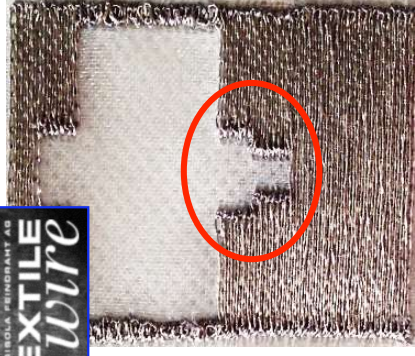
- **Thick (0.5mm-diameter)** E-threads consisting of 664 filaments
- **2 threads/mm** embroidery density



~1mm precision, cannot print sharp corners

New Technology

- **Thin (0.1mm-diameter)** E-threads consisting of 7 filaments
- **7 threads/mm** embroidery density



~0.1mm precision, can print sharp corners



Our latest embroidery process can achieve geometrical precision down to 0.1mm. Therefore, for the first time, accuracy of typical PCB prototypes can be achieved directly on textiles.

A. Kiourti and J.L. Volakis, "High-Geometrical-Accuracy Embroidery Process for Textile Antennas with Fine Details," *IEEE AWPL*, 2014.

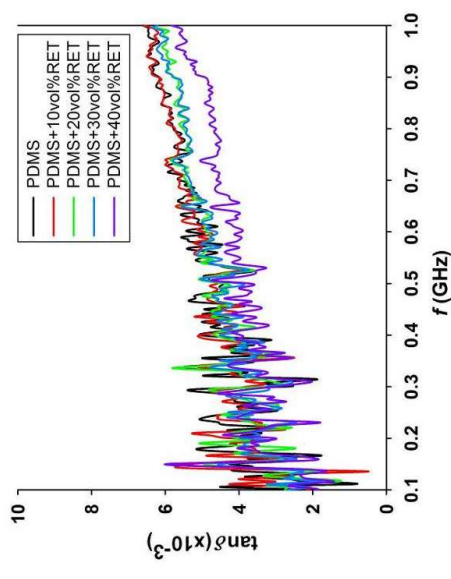
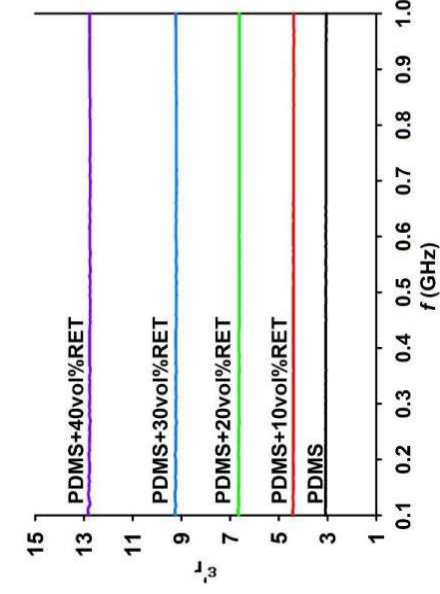
A. Kiourti, C. Lee, and J.L. Volakis, "Fabrication of Textile Antennas and Circuits with 0.1mm Precision," *IEEE AWPL*, 2015.

Polymer Substrates for Fully-Flexible Prototypes

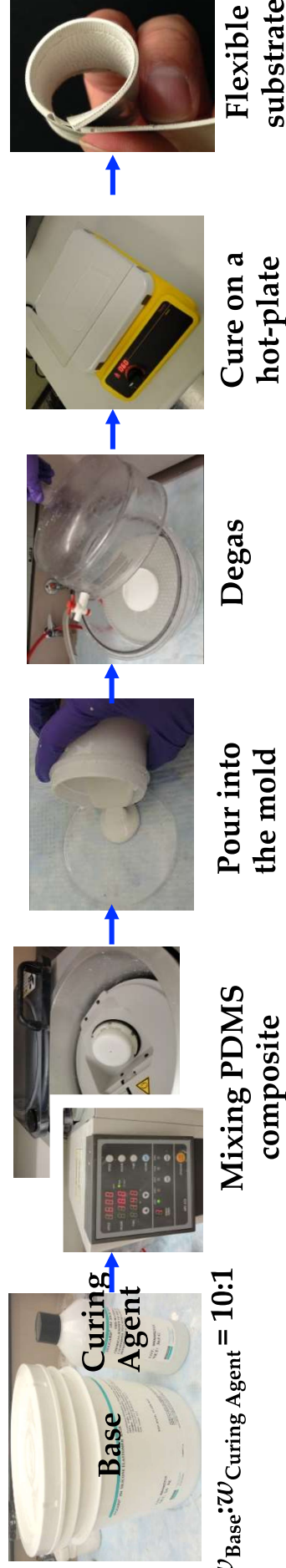
Composition: polydimethylsiloxane (PDMS) + rare earth titanate (RET)

Advantages of PDMS:

- Tunable in $\epsilon_r \sim 3$ to 12, low $\tan\delta < 10^{-2}$ up to GHz.
- Low temperature fabrication.
- Flexible and conformal
- Highly thermal/chemical stable.
- Hydrophobic: impermeable to water.



Fabrication





Comparison of our Technology vs. Other Reported Textile Surfaces

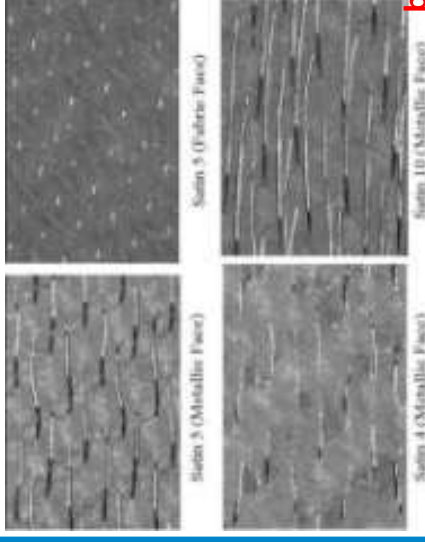
Metallized Textiles

- ⊖ Poor mechanical strength, especially when flexing.



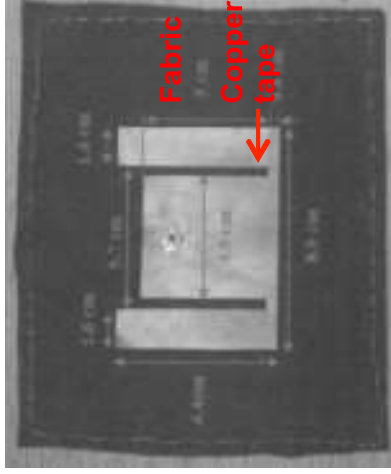
Embedded Metal Wires

- ⊖ Fatigue of metal threads, low metallization coverage.



Metal Foil

- ⊖ Possible delamination during flexing, due to mechanical difference btw Cu foil and fabrics.



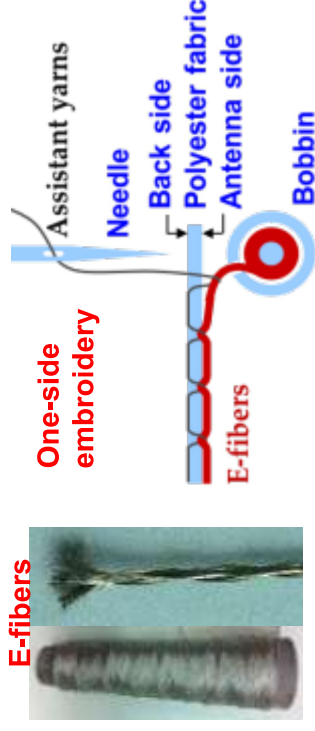
Other embroidered surfaces

- ⊖ Low surface conductivity. Dimension inaccuracy.



Embroidered E-threads (ESL, OSU)

- High strength fibers coated with metals.
- High conductivity from metal coating, structural integrity from fiber core..
- Fabrication via high-density sewing/stitching.



Embroidered antenna



- Highly flexible / conformal
- Light-weight
- Low conductor loss
- Excellent mechanical strength
- Accuracy of 0.1mm
- Stretchable, if need be
- Colorful, if need be

References:

a. S. Bashir, A. Chauraya, R.M. Edwards, J. Vardaxoglou, "A Flexible Fabric Metasurface for On Body Communication Applications," *Antennas & Propagation Conference*, Issue 16-17, 725-728, Loughborough, Nov. 2009.

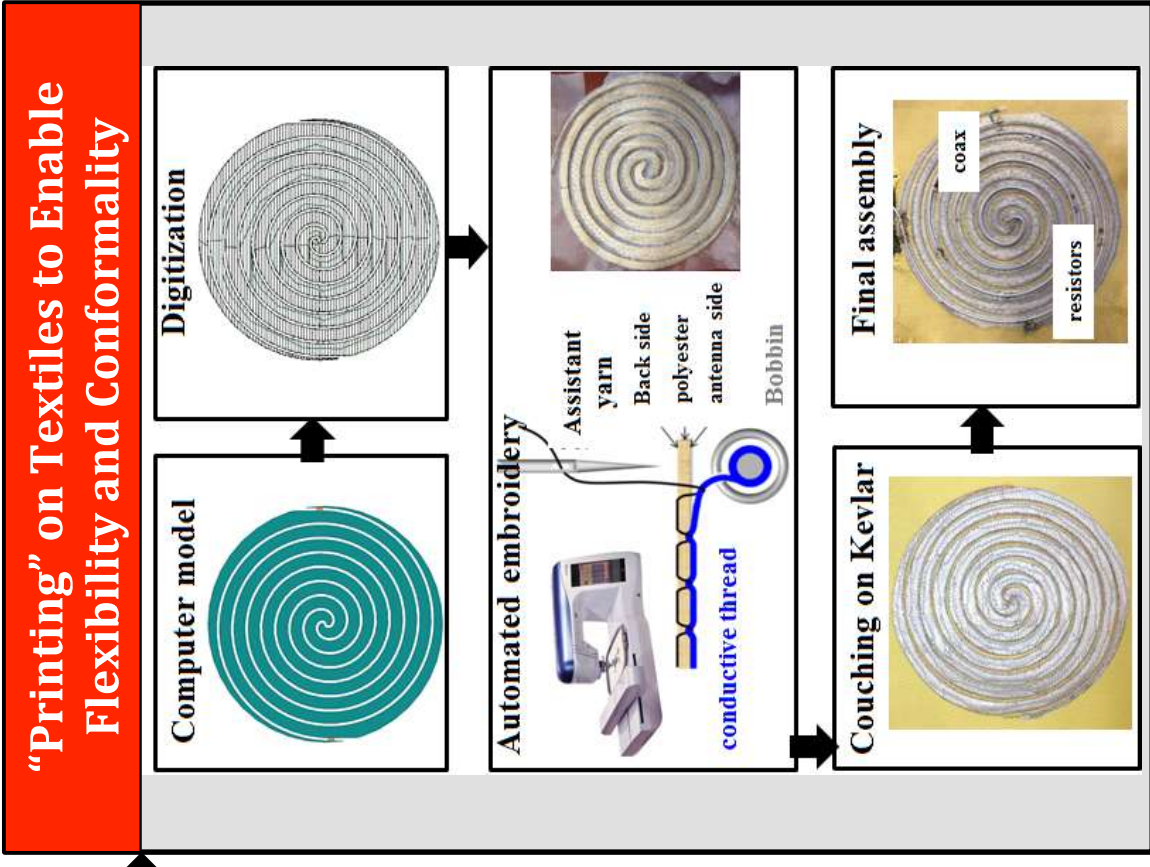
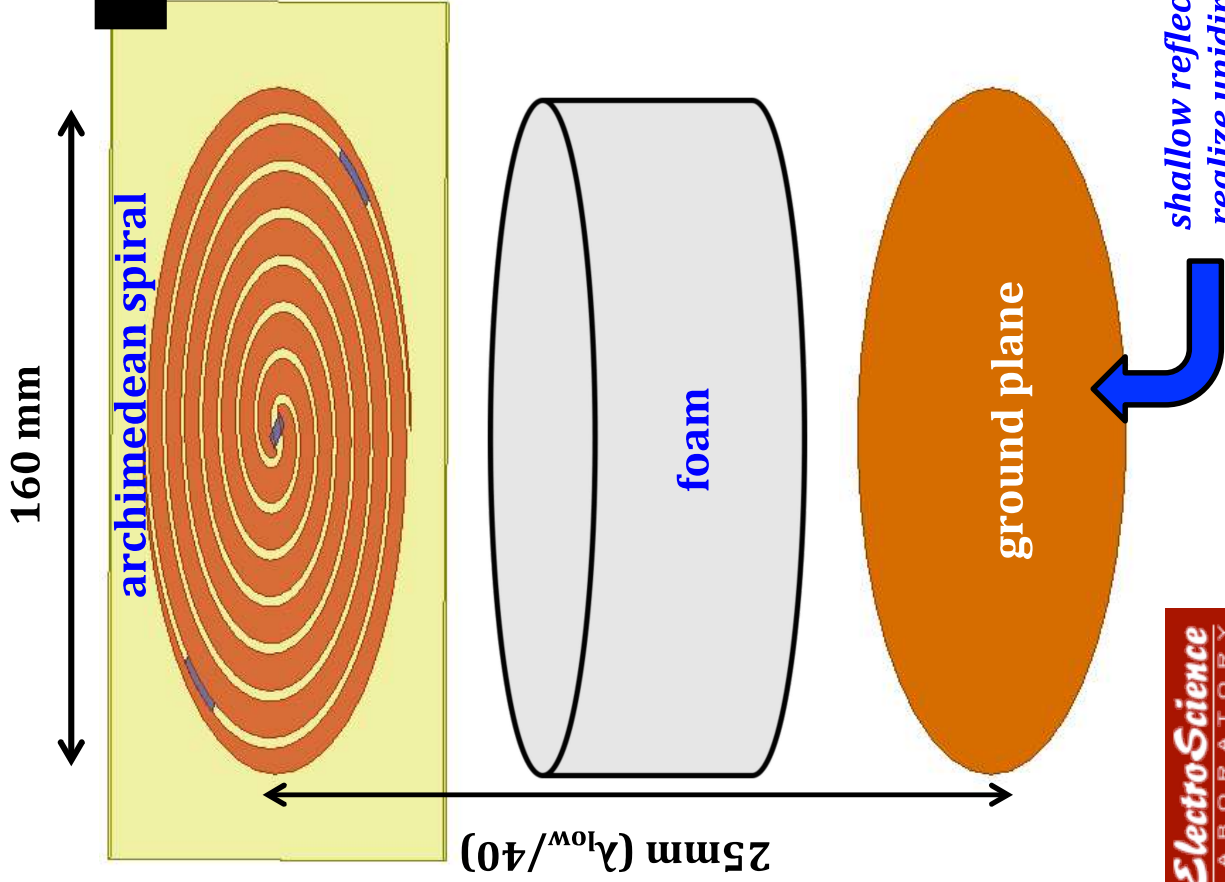
b. Y. Ouyang, W.J. Chappell, "High Frequency Properties of Electro-Textiles for Wearable Antenna Applications," *IEEE Transactions on Antennas and Propagation*, Vol. 56, Issue 2, 381-389, 2008.

c. P. Salomon, J. Kim, Y. Rahmat-Samii, "Dual-Band E-shaped patch wearable Textile Antenna," *IEEE Antennas and Propagation Society International Symposium*, Vol. 1A, 466-469, Jul. 2005.

d. G. Kim, J. Lee, K.H. Lee, Y.C. Chung, J. Yeo, B.H. Moon, J. Yang, H.C. Kim, "Design of a UHF RFID Fiber Tag Antenna with Electric-thread using a Sewing Machine," *Asia-Pacific Microwave Conference*, 1-4, Macau, Dec. 2008.

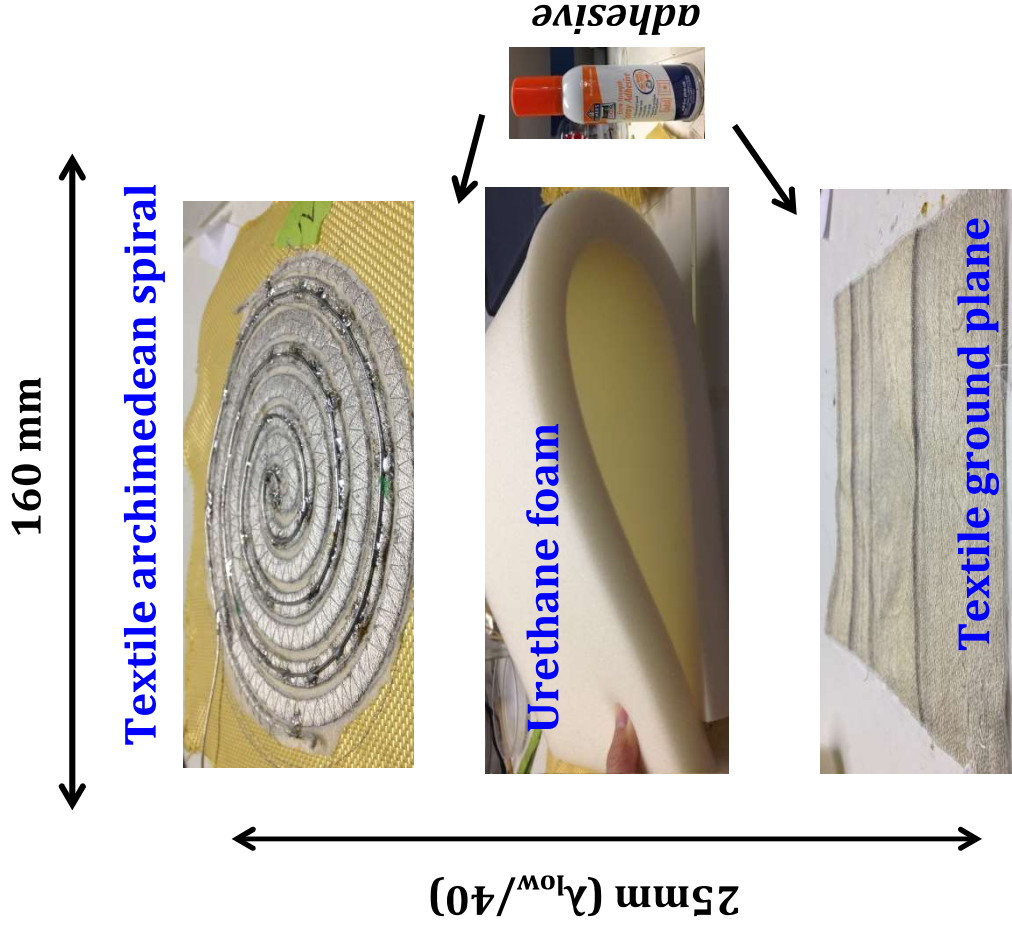


Proposed 10:1 Bandwidth Conformal Spiral Antenna: Design and Fabrication

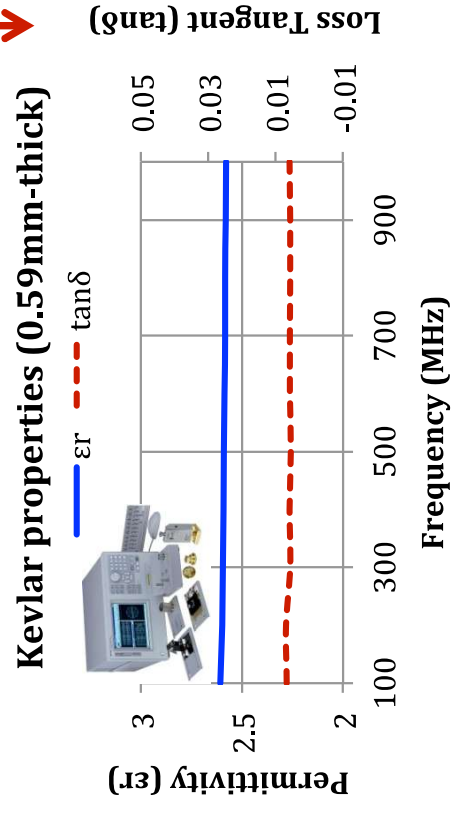




Conformal Spiral Antenna: Assembly Process



Our Selection	
E-fiber	7-filament Elektrisola (0.12 mm in diameter)
Fabric	Kevlar
Foam	Urethane Foam
Coaxial cable used as balun	RG58 semi-rigid, diameter = 0.116"
Adhesive	Elmer's board mate adhesive spray





Measurement Set-Ups Used to Evaluate the Spiral Antenna Performance

Measurement Set-Up A: Flat Spiral in Free-Space



Measurement Set-Up B: Bent Spiral on Metallic Cylinder



*metallic
cylinder is
used to
emulate the
UAV
platform*

Three spiral prototypes were tested for each measurement set-up:

Prototype 1: textile antenna

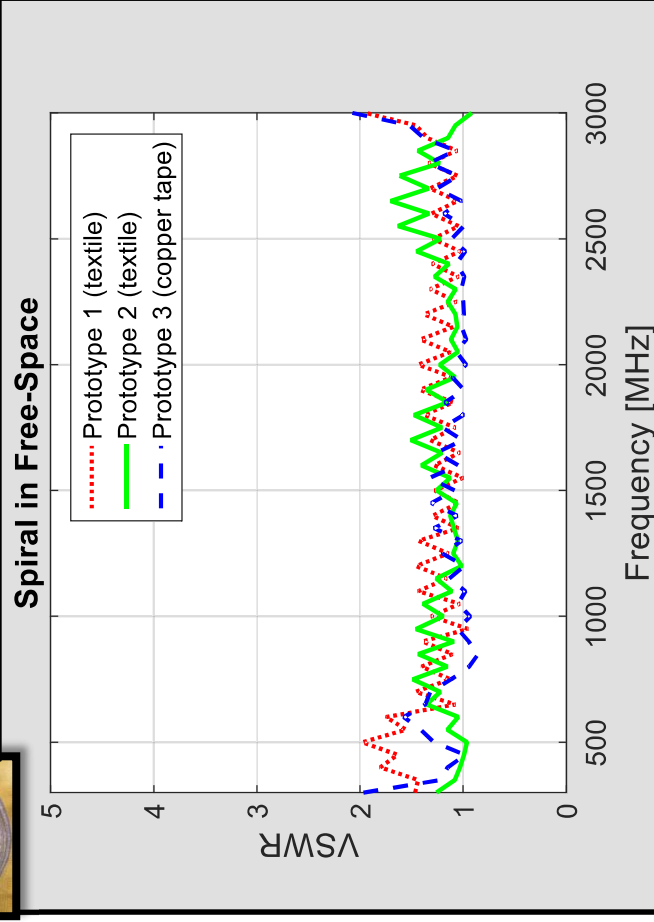
Prototype 2: textile antenna (identical to prototype 1 --- used to evaluate the repeatability of the employed fabrication process)

Prototype 3: copper tape antenna (spiral and ground planes made of copper tape --- used to validate the antenna performance vs. its copper equivalent)

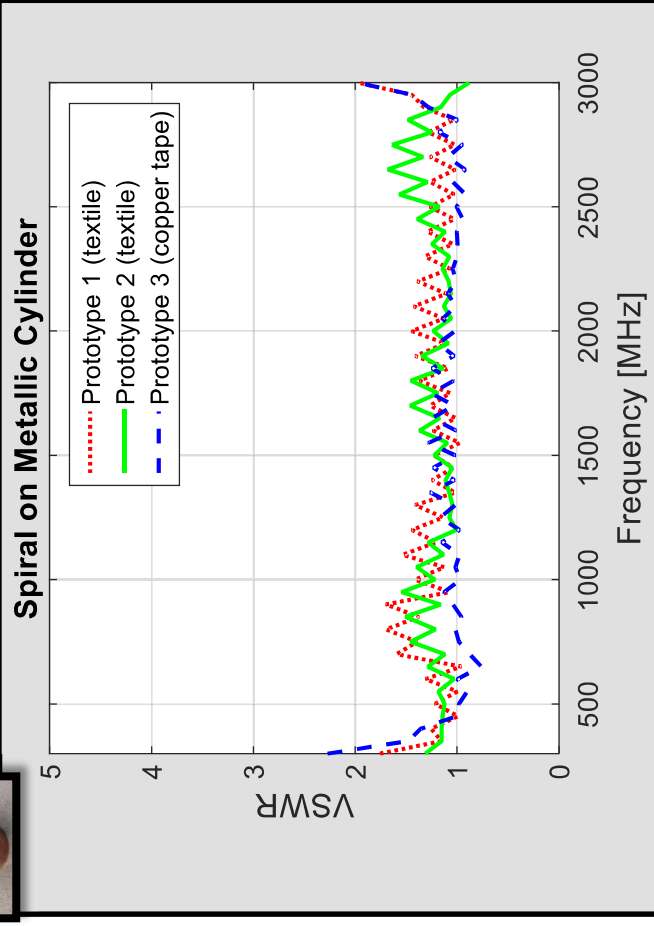
Measurement Results: VSWR



Measurement Set-Up A:
Flat Spiral in Free-Space



Measurement Set-Up B:
Bent Spiral on Metallic Cylinder

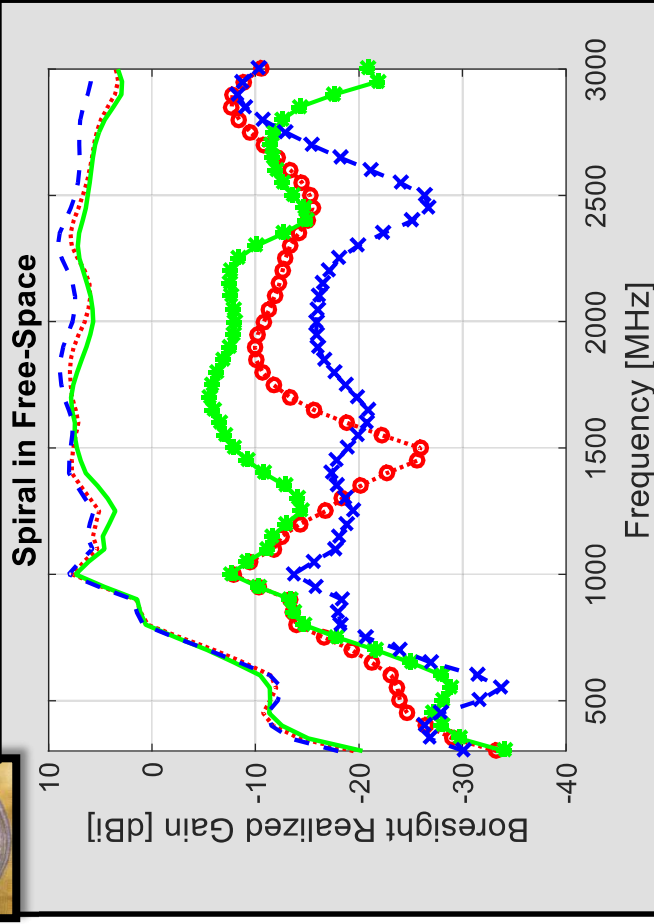


- The fabricated spiral exhibits a **10:1 bandwidth (VSWR<2)**, operating from 300MHz to 3GHz.
- When curved, the spiral **retains its wideband performance**.
- Prototypes 1 and 2 perform nearly the same, thus confirming **repeatability** of our fabrication approach. They also perform **similar to the copper tape antenna**.

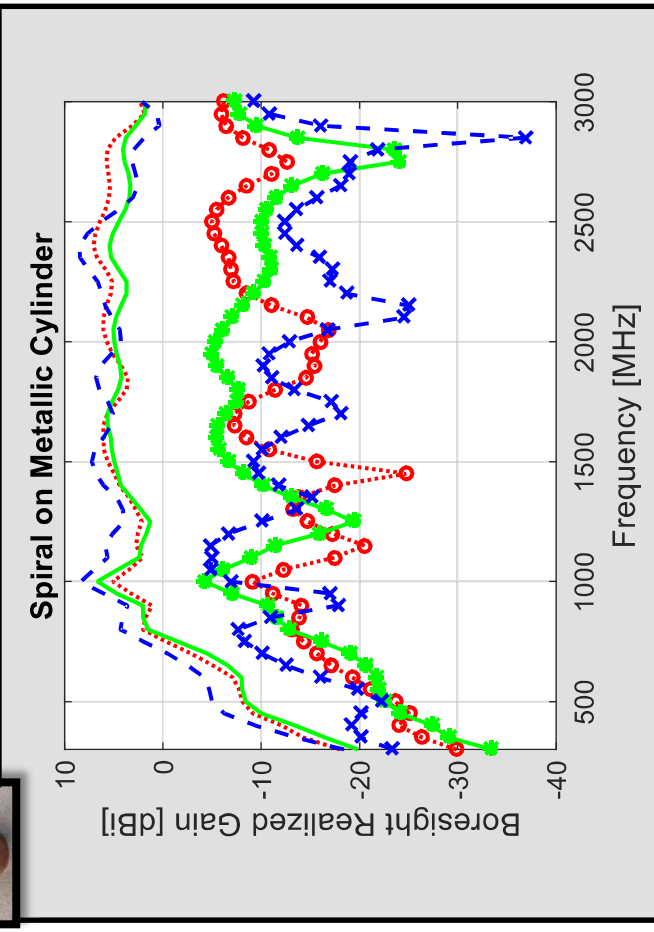
Measurement Results: Boresight Realized Gain



Measurement Set-Up A:
Flat Spiral in Free-Space



Measurement Set-Up B:
Bent Spiral on Metallic Cylinder



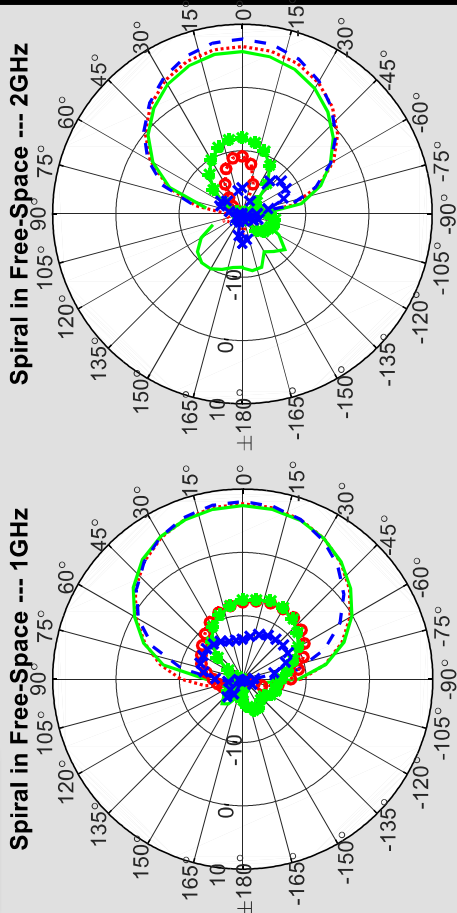
- Textile antennas exhibit **max. realized gain of ~7 dB** (up to ~2dB lower than the copper tape antenna).
- When curved, the spiral **retains its gain performance**.
- Prototypes 1 and 2 perform nearly the same, thus confirming **repeatability** of our fabrication approach. They also perform **similar to the copper tape antenna**.



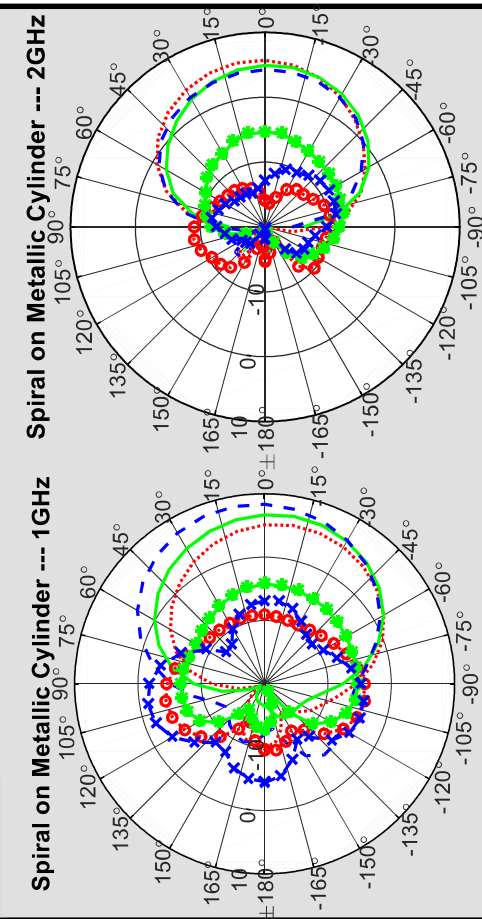
Measurement Results: Example Radiation Patterns



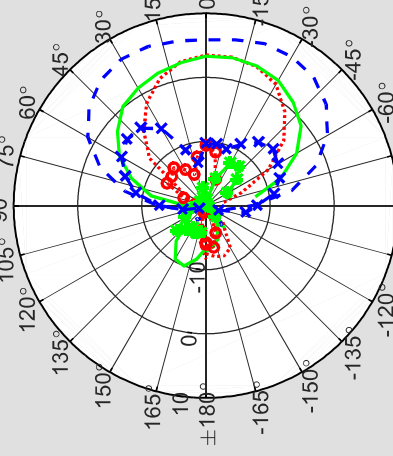
Measurement Set-Up A: Flat Spiral in Free-Space



Measurement Set-Up B: Bent Spiral on Metallic Cylinder

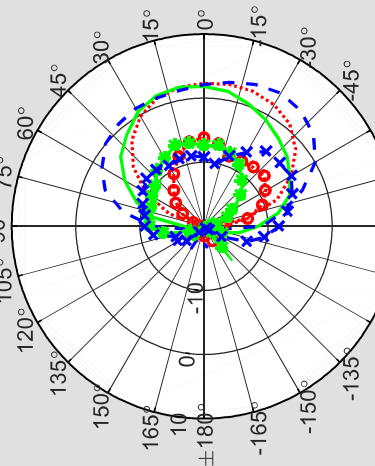


Spiral in Free-Space --- 3GHz



- Prototype 1 (textile) LHCP
- Prototype 2 (textile) LHCP
- Prototype 3 (copper tape) LHCP
- Prototype 1 (textile) RHCP
- Prototype 2 (textile) RHCP
- Prototype 3 (copper tape) RHCP

Spiral on Metallic Cylinder --- 3GHz

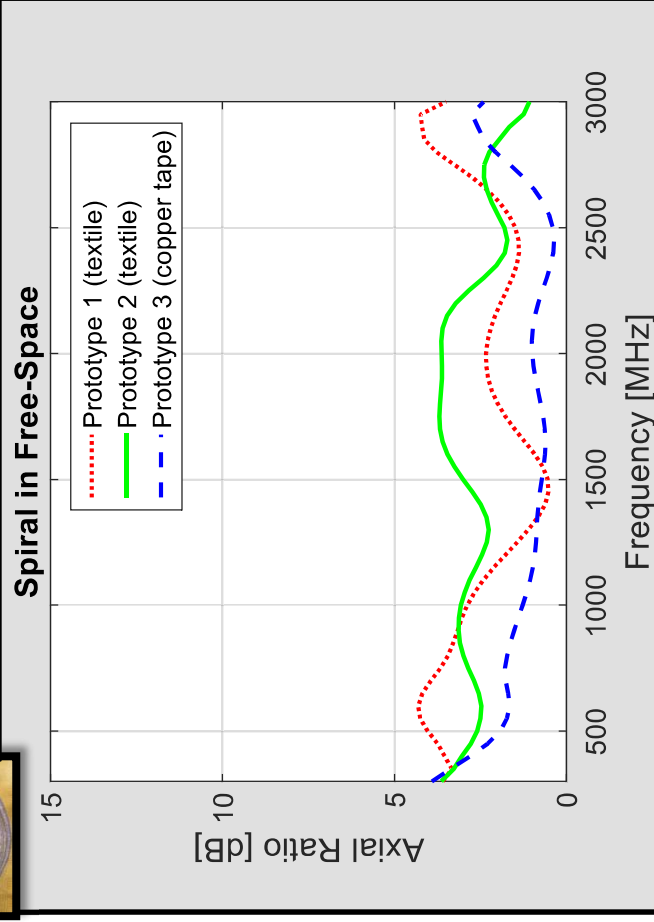


- The curved spiral's pattern is comparable to and broader than that of the planar configuration across the 10:1 band.

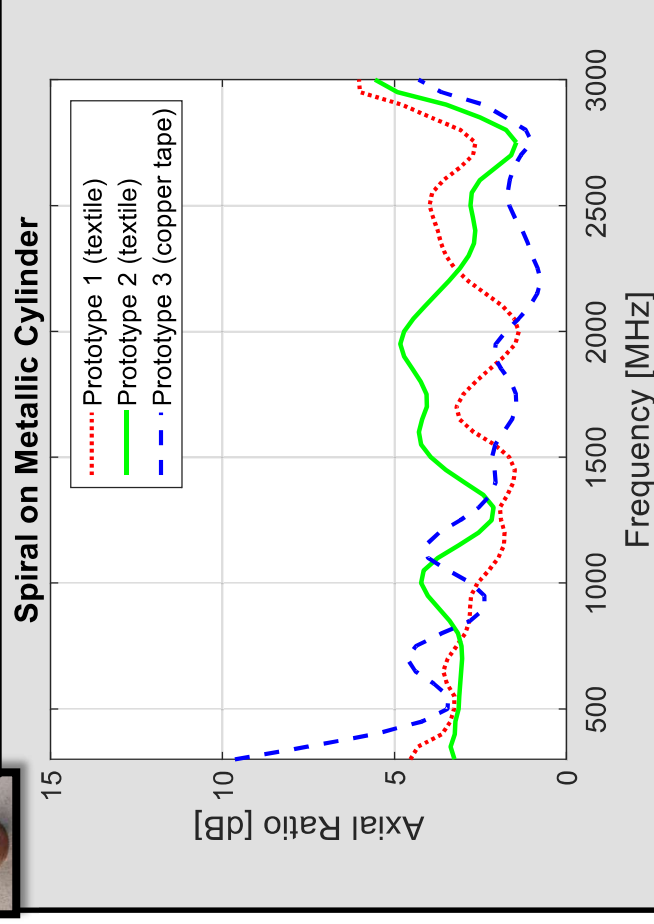
Measurement Results: Axial Ratio



Measurement Set-Up A:
Flat Spiral in Free-Space



Measurement Set-Up B:
Bent Spiral on Metallic Cylinder



- For the planar spiral, an **axial ratio of <3dB** was measured across almost the entire 10:1 band.
- For the curved spiral, the measured axial ratio was, in all cases, <5dB.
- Again, prototypes 1 and 2 perform nearly the same, thus confirming **repeatability** of our fabrication approach. They also perform **similar to the copper tape**

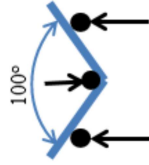


Mechanical and Thermal Testing

Mechanical Testing



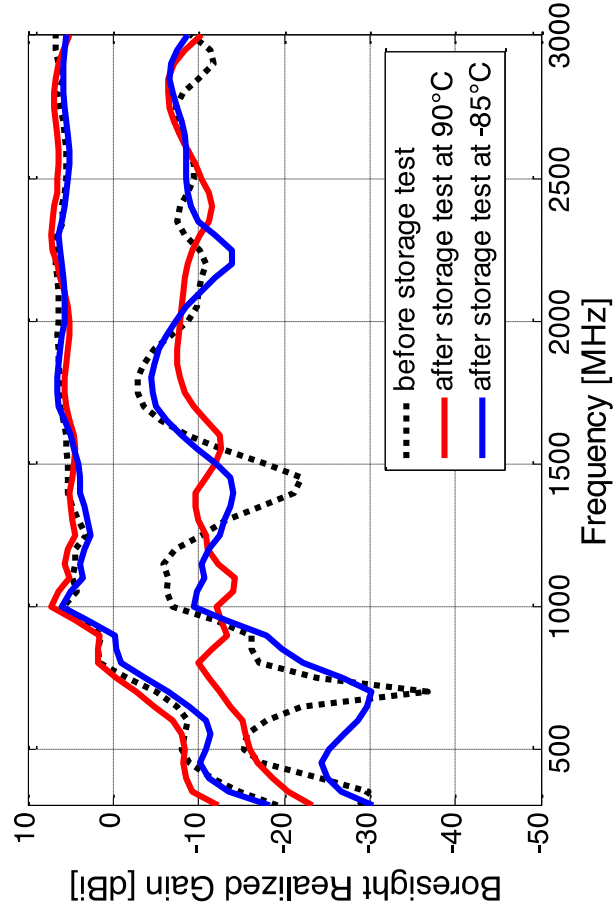
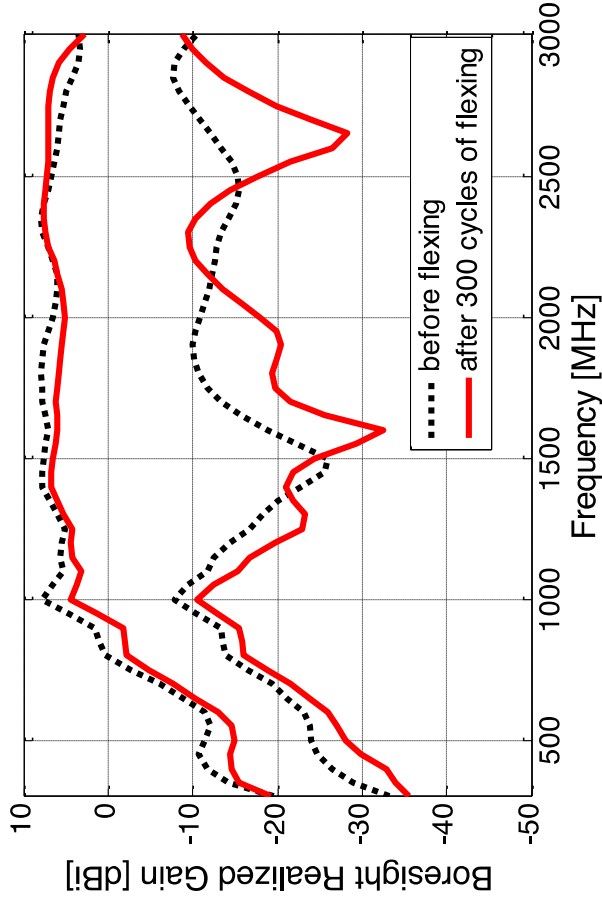
50 mm/min



Thermal Testing



- 2-hour hot storage test at 90°C, carried out at the OSU Materials Science Dept.
- 2-hour cold storage test at -85°C, carried out at OSU Biomed. Eng. Dept.



Questions?

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